NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3582

EFFECT OF CLIMB TECHNIQUE ON JET-TRANSPORT NOISE

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SUMMARY

A theoretical investigation of jet-transport climb techniques was made to determine the effect of variations in engine thrust and airspeed on sound-pressure levels heard by a ground observer.

Reducing either thrust or climb airspeed results in reduced sound-pressure levels. Reducing thrust decreases the sound power radiated; decreasing climb airspeed permits the initiation of climb sooner and hence results in increasing the source to observer distance. In general, minimum sound-pressure levels are obtained by using a combination of both minimum thrust and minimum climb speed consistent with safety considerations.

INTRODUCTION

Public acceptance of the jet transport during scheduled airline operations is expected to depend to a great extent upon the aircraft noise levels. Consequently, much thought and effort is being directed toward reducing the jet-noise nuisance, particularly in regions surrounding airports. In addition to current research on engine noise reduction, the control of the flight traffic pattern near airports is being considered as a method of reducing the noise.

Turbojet-engine noise measurements (refs. 1 to 3) have shown that engine noise is proportional to approximately the eighth power of the jet exit velocity; therefore, the most critical portion of the traffic pattern, to the noise-conscious public, will occur at high thrust during the initial climb.

Following take-off, the pilot has some latitude in the selection of flight speed and engine thrust, and it has been suggested that noise nuisance could be reduced by the proper selection of these parameters.

At climb airspeeds, the jet aircraft has a greater margin of thrust-minus-drag than an equivalent size piston-engine aircraft. It seems practical, therefore, to throttle the engine, within limits of safety, if such action will reduce the jet noise during climb. Noise attenuation due to the inverse-square distance relation would permit resumption of normal climb thrust when the aircraft reaches an altitude of 3000 to 5000 feet. Because the jet transport will cruise at altitudes above 30,000 feet and the normal rate of climb at cruise altitude is about one-fourth the sea-level rate, a moderate reduction of the climb rate at the low altitudes will not appreciably affect the over-all flight plan.

This report presents the effects of variations in flight speed and engine thrust upon the sound-pressure levels as sensed by a ground observer during the initial climb phase of jet-transport operation.

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The engine considered herein is a two-spool turbojet of current design operating without water-alcohol injection or afterburning. It is likely that this type of engine will be employed in the first generation of jet transports.

SYMBOLS

A wing area, W/wing loading, sq ft

C_D drag coefficient, D/q_0A

C_L lift coefficient, W/q_0A

D drag, C_Dq_0A, lb

ΔE increase in kinetic energy from take-off to 200-ft altitude, $(V_{200}^2 - V_T^2)/2g$, ft-lb/lb

F_j jet thrust, lb

F_n net thrust, lb

g gravitational acceleration, 32.2 ft/sec^2

M_0 flight Mach number

p_0 ambient static pressure, lb/sq ft

q_0 dynamic pressure, $0.7\ p_0M_0^2$, lb/sq ft

V_j jet velocity, $F_j g/w$, ft/sec

V_0 flight speed, ft/sec

V_T take-off airspeed, ft/sec

V_{200} airspeed at 200-ft altitude, ft/sec

W airplane weight

w engine mass flow, lb/sec

The decibel as used herein is referenced to 0.0002 dynes/sq cm or 10^{-13} watts.

ENGINE AND AIRPLANE PERFORMANCE CHARACTERISTICS

In order to make this analysis, a typical airplane-engine combination was chosen, and the sound-pressure levels that result from variations in climb technique were calculated.

Airplane configuration. - The following airplane design assumptions were made:

(1) Four-engine swept-wing jet transport with high subsonic cruise speed

(2) Gross weight, 160,000 pounds

(3) Gross weight divided by take-off thrust, 4.0

(4) Wing loading, 65 pounds per square foot

Engine parameters. - In order to compute climb rates and jet velocities, the engine performance must be known as a function of flight speed and percent thrust. It is assumed that the engine is equipped with a constant-area exhaust nozzle. At rated conditions, the sea-level variation of net (propulsive) thrust ratio with flight speed is shown in figure 1. Net thrust initially decreases as flight speed increases and reaches a minimum of 88 percent thrust at a flight speed of 260 knots; thereafter, thrust increases with flight speed so that net thrust at 500 knots is 93 percent of the static value. This curve was obtained from engine pumping characteristics and is typical of most current turbojet engines; however, at flight speeds above 500 knots, the net thrust curves will vary among different engines.

Engine mass-flow ratio is also shown in figure 1. Mass-flow ratio is defined as the ratio of mass flow at a given flight speed to the mass flow at zero flight speed. These data were calculated from a plot of sea-level corrected mass flow as a function of corrected engine speed. Engine mass flow increases as airspeed, or inlet total pressure, increases, reaching a value at 500 knots that is 19 percent greater than the static value.

Take-off and climb technique. - All calculations were made assuming sea-level take-off under standard atmospheric conditions. The airplane was assumed to be airborne at 120 knots after about a 4000-foot ground run. The airplane then climbed to 200-feet altitude and accelerated to 150 knots true airspeed. In each case, maximum dry thrust was utilized during the take-off roll and maintained throughout the transition climb to 200-feet altitude. In order to reduce the airplane drag variables in this analysis, the landing gear and wing flaps were assumed fully retracted when the airplane reached 200-feet altitude and 150 knots. After this point in the flight path nine climb techniques were assumed for these calculations: climb speeds of 150, 250, and 350 knots at each of three thrust conditions, 60, 80, and 100 percent of maximum dry thrust. Acceleration to the higher climb speeds (greater than 150 knots) was accomplished during level-flight maximum-thrust conditions, at an altitude of 200 feet. An average headwind of 15 knots was assumed during this analysis.

Rate of climb and flight path. - The rate of climb and flight path were computed for each of the climb techniques. All rate-of-climb calculations were based on standard atmospheric conditions at an average climb altitude of 2000 feet. At each climb condition, it was possible to calculate rate-of-climb from the following formula:

$$\text{Rate of climb} = \frac{(V_0)(F_n - D)}{W}, \text{ ft/sec}$$

where net thrust was obtained by adjusting standard sea-level static thrust to a static thrust at 2000-feet altitude, and then applying a Mach number or flight-speed correction obtained from figure 1. Airplane drag coefficient was obtained from the following parabolic lift-drag relation:

$$C_D = \frac{C_L^2 + 0.18}{20}$$

This relation was chosen as being realistic for a swept-wing jet transport operating at speeds below the transonic drag-rise speed. A plot of rate of climb with flight speed (fig. 2) shows that the maximum rate of climb at 2000-feet altitude occurs at a true airspeed of 430 knots. When fuel consumption is the only consideration, high fuel consumption at low altitude dictates that jet aircraft climb at the airspeed which results in maximum climb rate.

Figure 2 also shows the variation of rate of climb with engine thrust at different flight speeds. At 150-knots climb speed, an engine thrust reduction from maximum to 60-percent thrust caused a decrease in climb from 2430 to 1120 feet per minute. The specific fuel consumption can be assumed constant throughout this range of engine thrusts. A 40-percent reduction in thrust when coupled with the corresponding 54-percent reduction in climb rate indicates that there will be a slight increase in fuel consumed for equal altitude coverage. Similar analyses at 250 and 350 knots give the same sort of results in terms of fuel required.

In order to plot flight paths, the horizontal distances required during the transition climb to 200-feet altitude and level flight acceleration to the higher climb speeds must be computed. The following distance formula was used (ref. 4).

$$\text{Distance} = \frac{W}{F_n - D} (200 + \Delta E)$$

The thrust and drag terms are computed at mean flight speed. The kinetic energy term ΔE is based on flight speeds corrected for wind velocity. As shown in figure 3, a flight speed of 150 knots is attained at a dis-of $1\frac{3}{8}$ miles from brake release, but $5\frac{3}{4}$ miles is required for airplane acceleration to 350 knots. Different climb techniques result in aircraft altitudes from 700 to 5600 feet at a distance of 7 miles from brake release.

NOISE-LEVEL CALCULATIONS

Sound-pressure levels. - In order to estimate the sound-pressure levels from a jet transport, the sound field of a single 10,000-pound-thrust engine is first considered. The single-engine sound field was obtained from an engine mounted in an open-air thrust stand at the Lewis laboratory. Since the airplane utilizes four engines, it was assumed that the sound power was quadrupled. The sound-pressure levels for the four-engine airplane will be 6 decibels greater than the values measured around the thrust stand. Although the engines were mounted in four separate pods, a point source is assumed for distance calculations. The estimated sound field 200 feet from a four-engine jet transport is shown in figure 4. The actual sound measurements were taken in the horizontal plane and axial symmetry is assumed. A maximum sound-pressure level of 133 decibels occurs between 30° and 40° from the jet direction, and is 13 decibles higher than any sound-pressure level in the forward quadrants.

Engine-sound spectrum level at the 45° azimuth is plotted in figure 5. Herein, spectrum level is the sound pressure in a one-third octave band corrected to a unit frequency. This spectrum of the maximum sound pressure indicates that jet noise is predominantly low-frequency noise.

Complete descriptions and formulas for the acoustic terms used herein are given in reference 5.

Attenuation due to distance. - Sound levels as sensed by a ground observer will depend on aircraft altitude, airspeed, and thrust. Sound-pressure measurements obtained during several overhead aircraft passes have shown that sound attenuation obeys the inverse-square distance relation; that is, sound pressure level is reduced 6 decibels whenever altitude is doubled. The inverse-square relation is plotted in figure 6. The reference altitude of 200 feet corresponds to the observer distance during sound-field measurements in figure 4. Turbojet sound directionality is such that the maximum sound-pressure level heard by an observer will be transmitted after the aircraft has passed overhead and the observer is 40° from the jet axis. Because of this angular relation, 4 decibels must be added to the altitude attenuation.

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Attenuation due to airspeed. - Recent sound measurements made during low-altitude-aircraft passes at the Lewis laboratory showed that sound-pressure levels were proportional to the eighth power of the relative jet velocity $(V_j - V_0)$ as given by the following equation:

$$\Delta db = 10 \log \left(\frac{V_j - V_0}{V_{j,V=0}}\right)^8$$

The relative velocity was computed as the quotient of net thrust and engine mass flow. Thrust and mass flow were determined by a procedure previously described in the "Engine parameters" section. The relation between jet-noise attenuation and flight speed is shown in figure 7. Increasing flight speed from zero to 250 knots results in a sound-pressure reduction of 6 decibels, which is equivalent to the attenuation obtained when altitude is doubled.

Attenuation due to thrust reduction. - Sound attenuation due to thrust reduction was calculated assuming the eighth-power relation between sound power and relative jet velocity. Figure 8 shows this attenuation in terms of total sound power as obtained from velocity calculations and also as measured from an engine in an open-air thrust stand. The theoretical curve, which was calculated from jet velocity, falls about 1/2 decibel below the measured values. One-half decibel is of the same order of magnitude as accuracy of measurement. Total sound power was obtained by integrating the sound pressures around the engine by a method described in reference 5. Since the sound pressure at 40° was the maximum emitted by the engine, it had a large influence on total sound power. For this reason, reductions in total sound power at partial thrust were identical (decibel wise) to sound-pressure level reductions at the critical 40° angle. If it is assumed that sound direction does not change significantly for the flight speeds under consideration, the theoretical curve in figure 8 can be used to determine the amount of sound-pressure reduction due to throttled engine operation. A 28-percent reduction in thrust results in a 6-decibel reduction in sound pressure or is equivalent to doubling the aircraft altitude.

The variation of sound pressure with flight speed and thrust is shown in figure 9. At increased airspeeds, throttled engine operation causes greater sound attenuation. At static conditions, there is a $9\frac{1}{2}$-decibel reduction when the engine is throttled to 60 percent thrust, but at 350 knots, a 12-decibel reduction should be realized.

Resulting sound-pressure levels. - Maximum sound-pressure levels were calculated at various ground observer locations. The attenuations due to altitude, airspeed, and partial thrust were subtracted from the reference level of 133 decibels, and the resulting levels are shown in figure 10. In order to eliminate the need for estimating the near-field noise levels under the aircraft during transition climb immediately following take-off, sound levels 200 feet (normal to flight path) from the airplane are shown. At most airports this transition climb can be made within the field boundary.

It is readily apparent that the lowest flight speed results in much lower noise levels during a considerable portion of the initial climb. Figure 3 shows that at a given thrust the lower airspeeds are associated with the higher flight paths. At constant altitude, jet noise is attenuated by higher flight speeds; however, during climb, the combination of low flight speed and higher altitudes results in much greater attenuation. If climb speed is reduced from 250 to 150 knots, there is at least a 17-decibel reduction in ground sound-pressure level at a distance of 3 miles from brake release.

When the engines are initially throttled, considerable reduction in sound level occurs as indicated by the steeper straight portions of the curves. The time required to throttle to 60 percent thrust was assumed as 3 seconds. The initial benefit from reduced thrust is later somewhat offset because the lower flight paths result in less altitude attenuation. At 150 knots the acoustic benefits gained from a 20-percent thrust reduction are probably insignificant, but 4- or 5-decibels attenuation are realized at 40-percent thrust reduction. This is not a large improvement, and its merits would have to be weighed against the potential hazard of flying at slow speed at low altitude above populated areas. A larger thrust reduction would result in lower sound levels, but the climb rate at 60-percent thrust is probably the minimum acceptable. A climb airspeed of 150 knots is probably the minimum acceptable from three-engine considerations.

For the airplane-engine combination assumed, reduced airspeed should be maintained until only 4 or 5 miles from brake release, at which point the ground noise level would be about 100 decibels. The maximum sound-pressure level heard by a ground observer is 100 decibels when a 10,000 horsepower piston-engine transport passes overhead at an altitude of about 1200 feet.

Figure 10 does not show duration of the noise. Although duration of a given sound level will be greater at the lower flight speeds, maximum sound-pressure level is believed to be the more critical parameter throughout the range of airspeeds considered.

In summary, the optimum climb technique from the standpoint of lowest ground noise levels would consist of the lowest climb airspeed and the lowest thrust compatible with safety.

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CONCLUSIONS

An analysis of jet-transport climb techniques based on the assumed airplane-engine configuration leads to the following conclusions:

1. Reducing either thrust or climb airspeed results in reduced sound-pressure levels. Reducing thrust decreases the sound power radiated; decreasing climb airspeed permits the initiation of climb sooner and hence results in increasing the source to observer distance. In general, minimum sound-pressure levels are obtained by using a combination of both minimum thrust and minimum climb speed consistent with safety considerations.

2. An increase in flight speed from zero to 250 knots causes a sound-pressure reduction of 6 decibels, which is equivalent to doubling the aircraft altitude.

3. At 150 knots airspeed and constant altitude, a 40-percent reduction in thrust results in a 10-decibel noise reduction.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 13, 1955

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5. Bolt, R. H., Lukasik, S. J., Nolle, A. W., and Frost, A. D., eds.: Handbood on Acoustic Noise Control. Vol. I. Physical Acoustics. WADC Tech. Rep. 52-204, Aero. Medical Lab., Wright Air Dev. Center, Wright-Patterson Air Force Base, Dec. 1952. (Contract No. AF 33(038)-20572, RDO No. 695-63.)

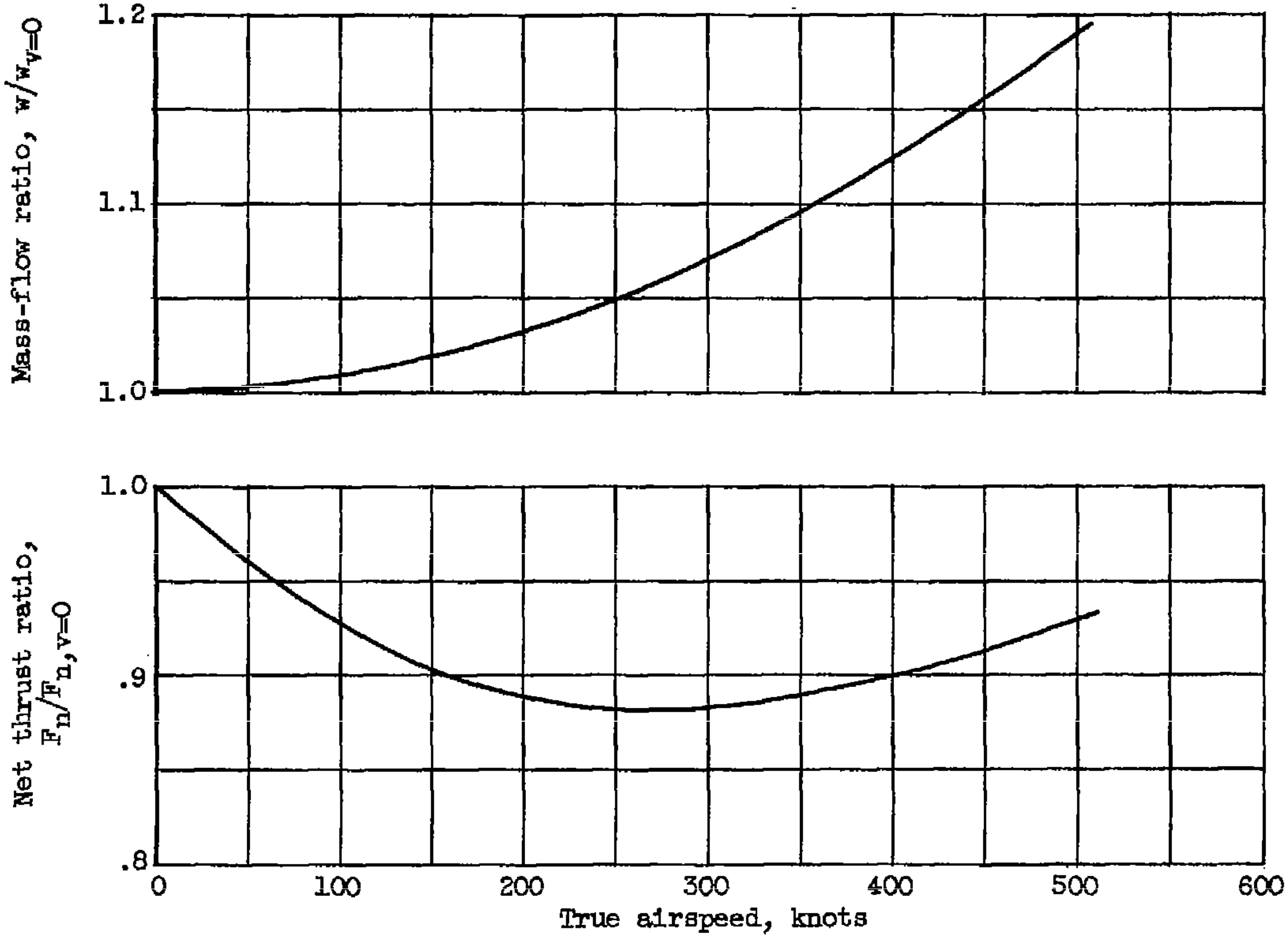

Figure 1. - Variation of mass-flow ratio and net thrust ratio with flight speed at sea-level maximum thrust.

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CQ-2 back

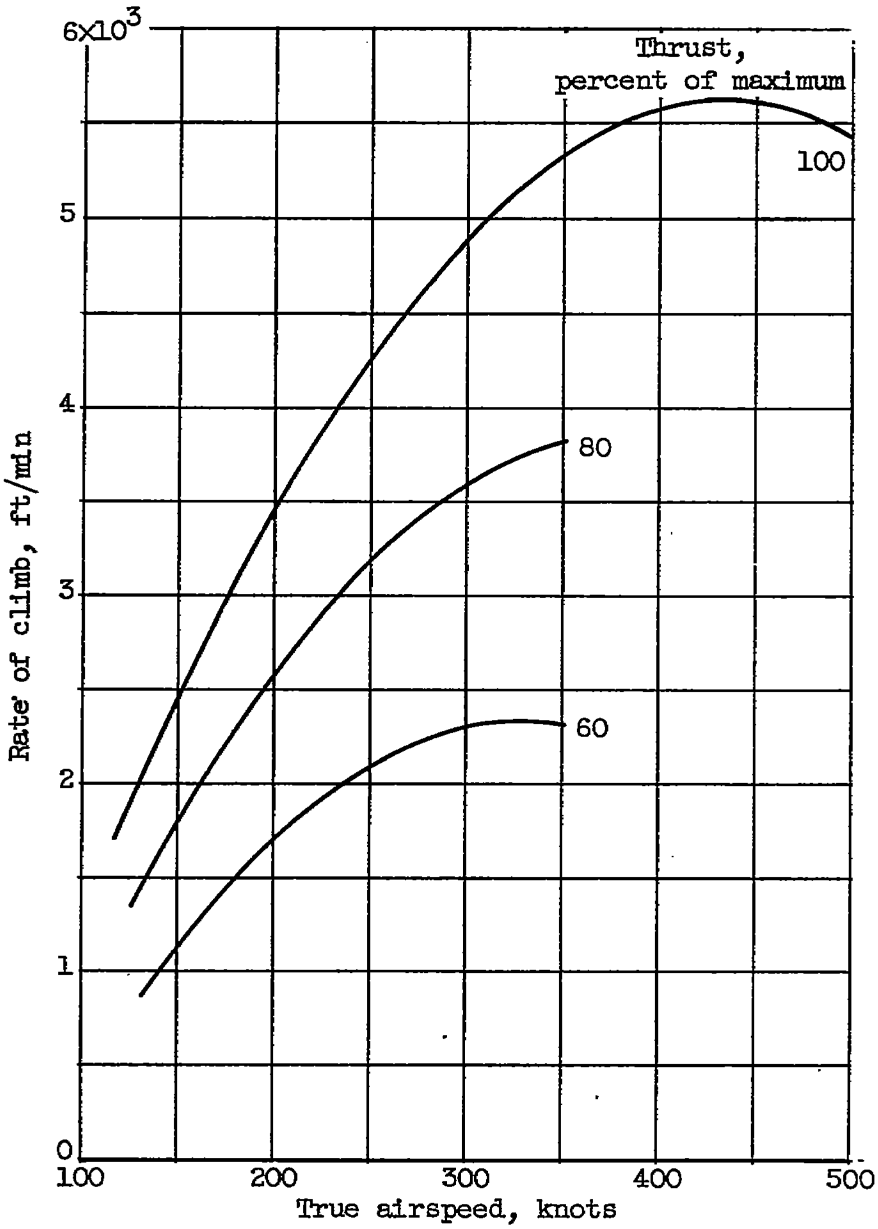

Figure 2. - Variation of rate of climb with flight speed and thrust.

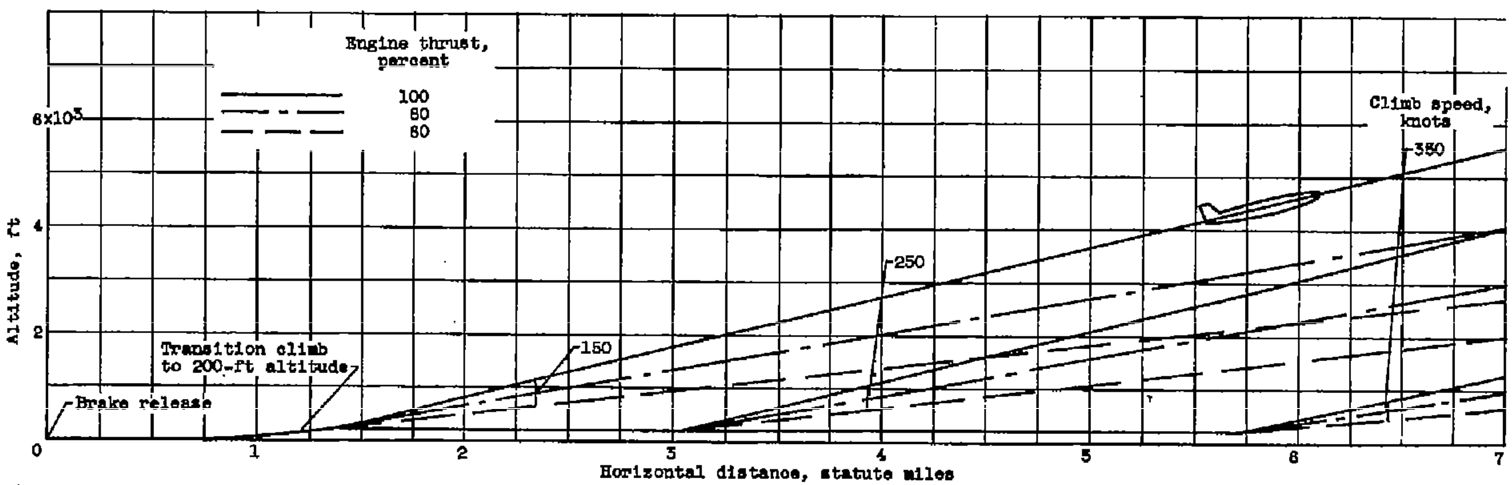

Figure 3. - Aircraft flight paths at various values of engine thrust and climb speed. Gross weight divided by take-off thrust, 4.0; wing loading, 65 pounds per square foot; $C_D = (C_L^2 + 0.18)/20$.

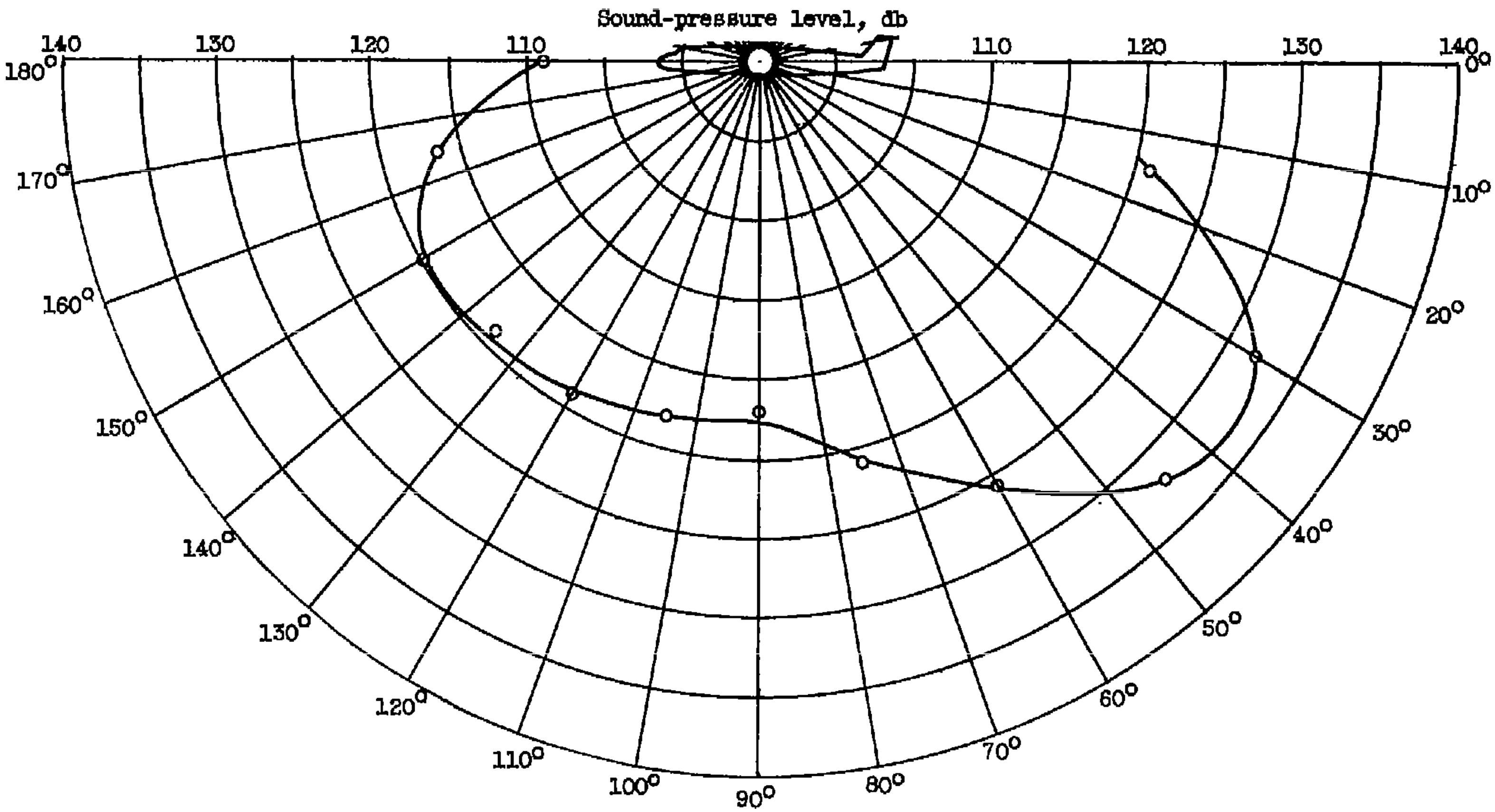

Figure 4. - Estimated sound field 200 feet from four-engine jet aircraft. Sea-level static conditions.

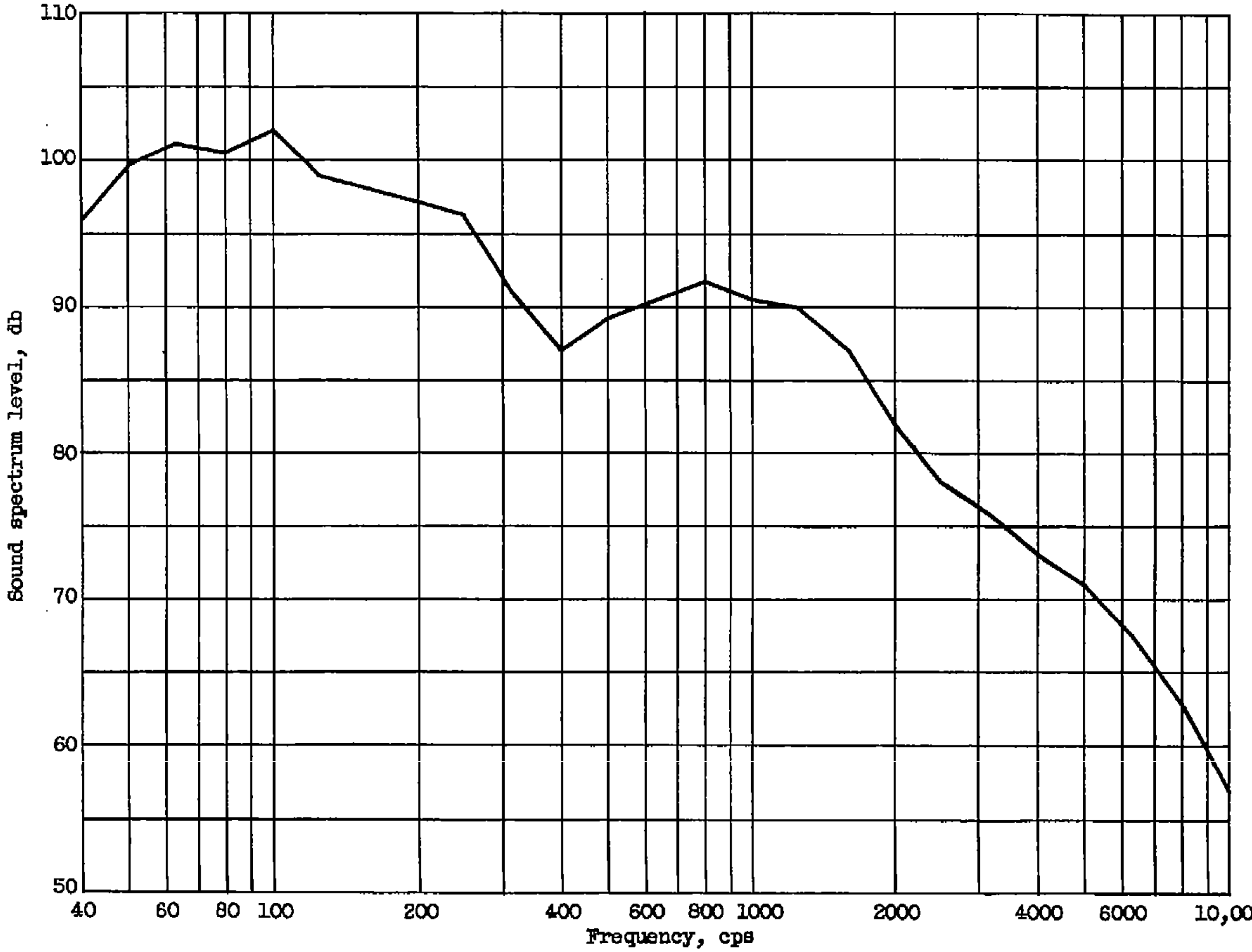

Figure 5. - Sound spectrum levels obtained at maximum dry thrust 200 feet from engine on 45° azimuth.

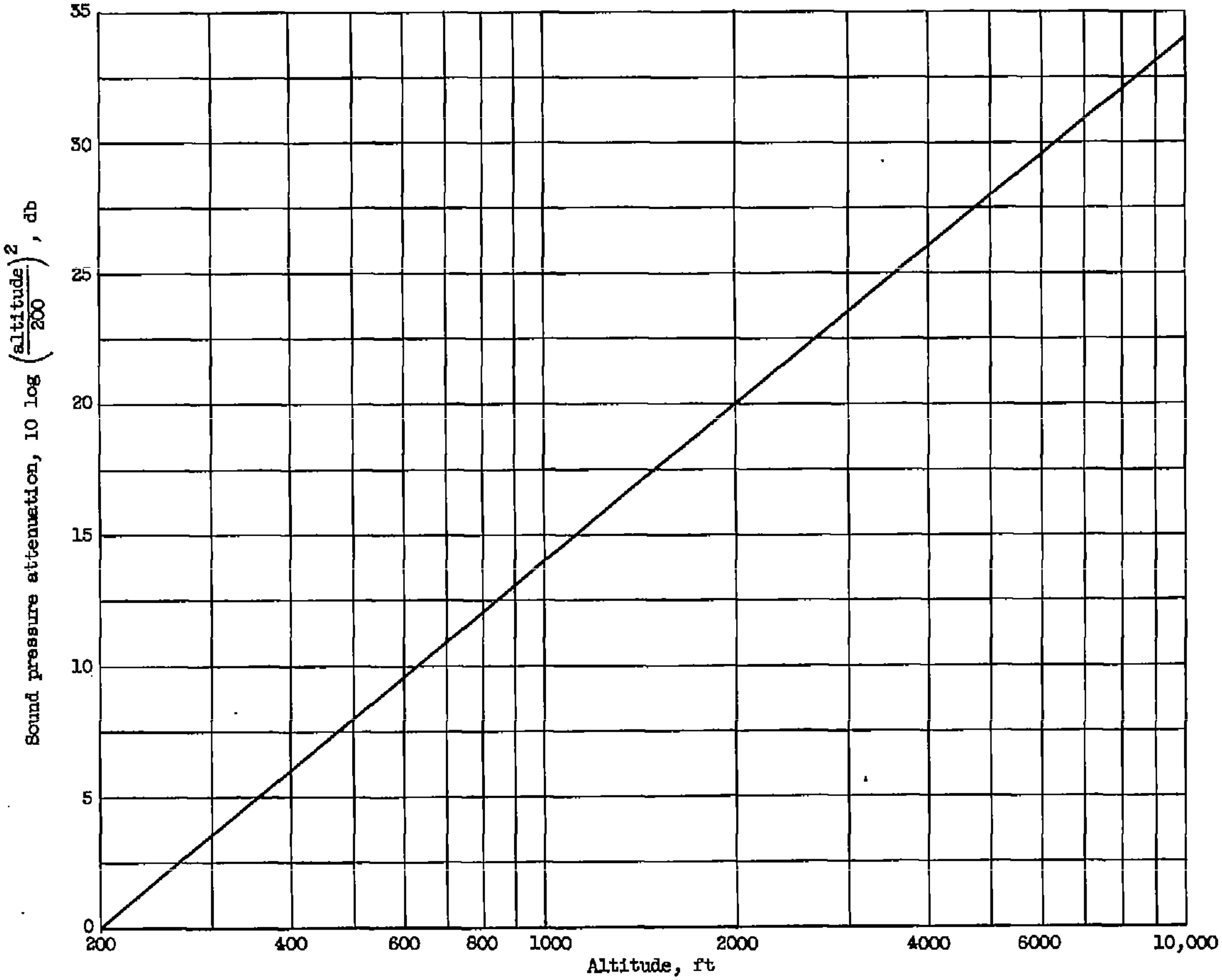

Figure 6. - Sound-pressure attenuation due to altitude. Reference altitude, 200 feet.

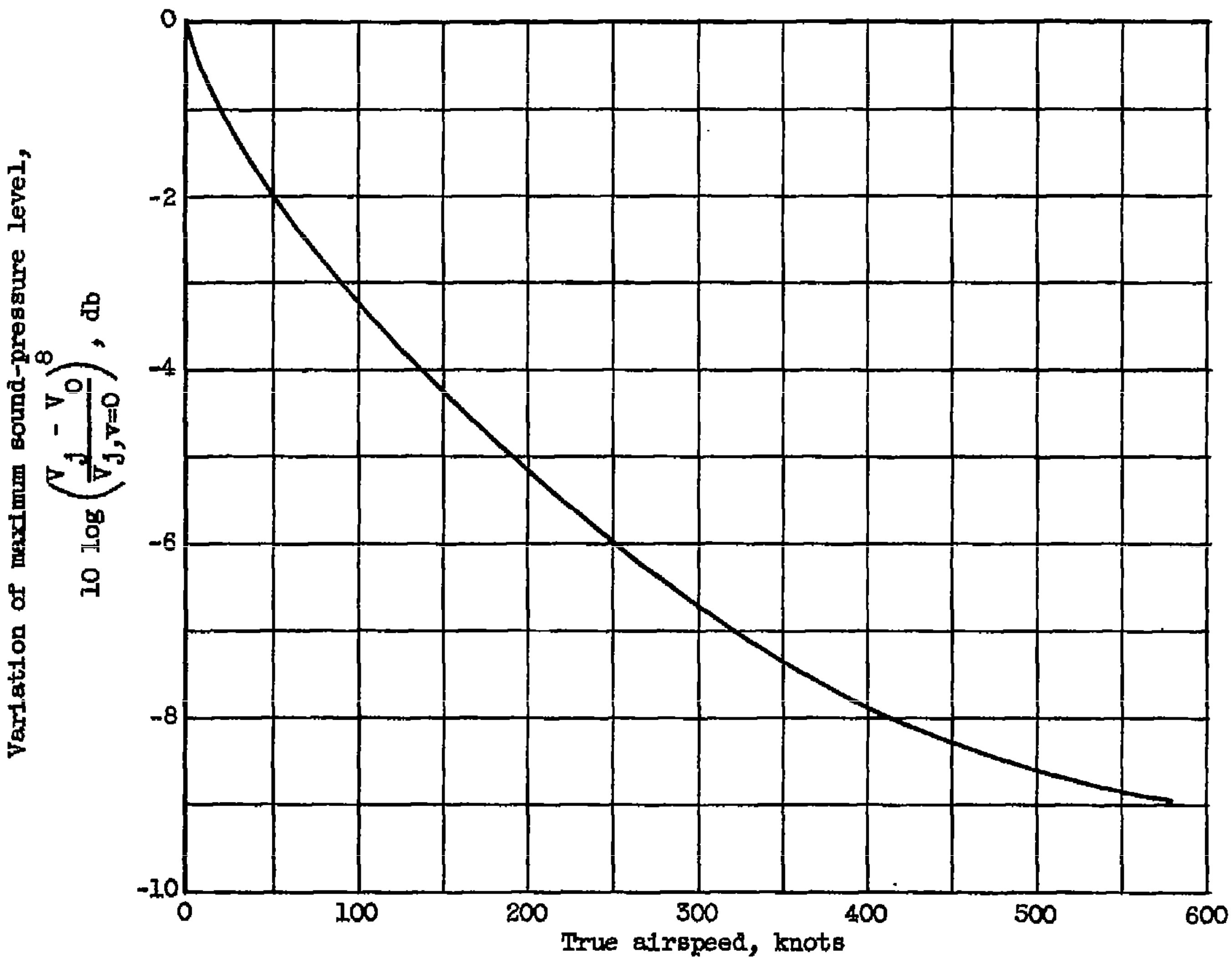

Figure 7. - Sound-pressure attenuation due to flight speed at maximum sea-level dry thrust.

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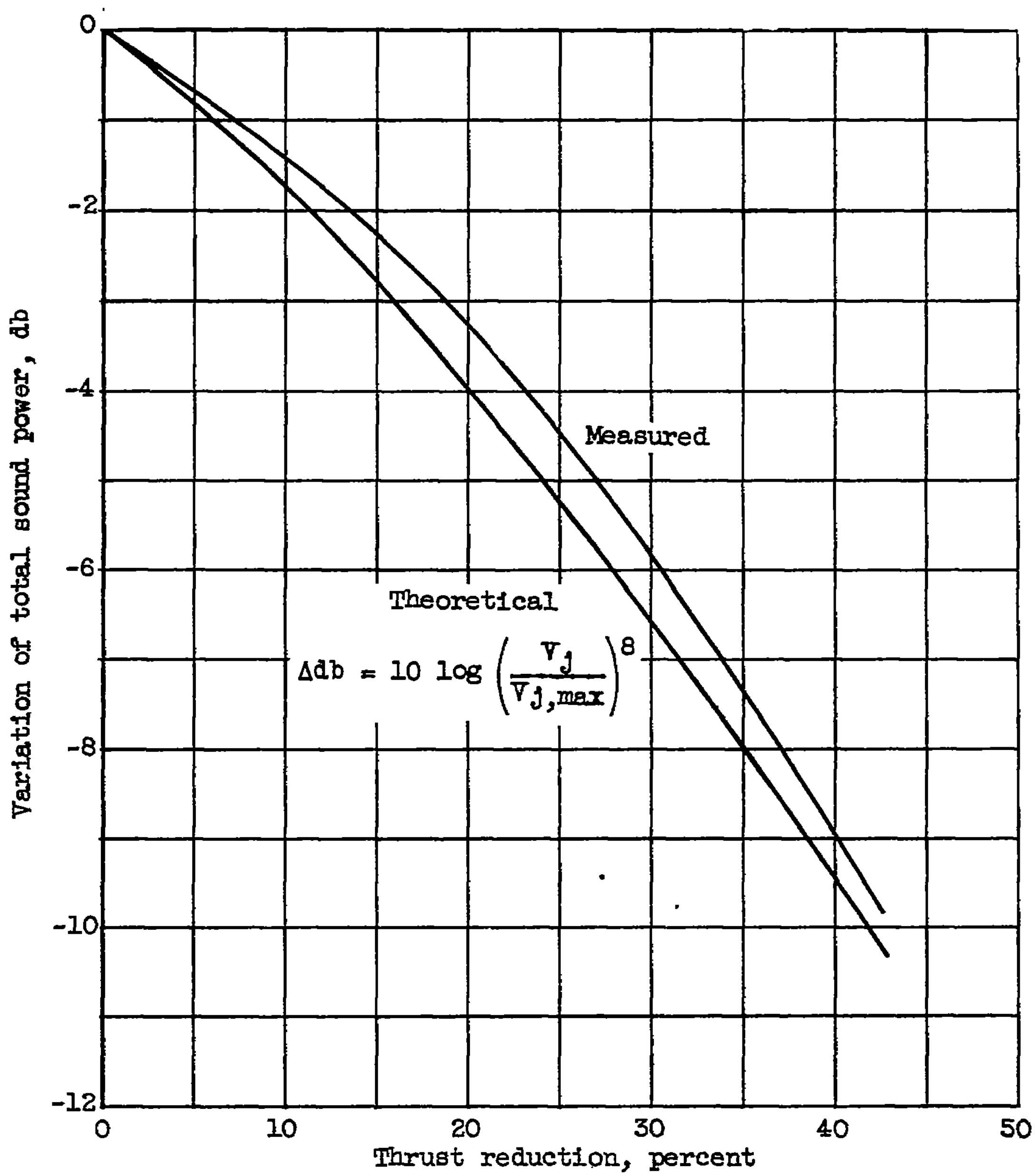

Figure 8. - Relation between total sound power and sea-level, static thrust condition.

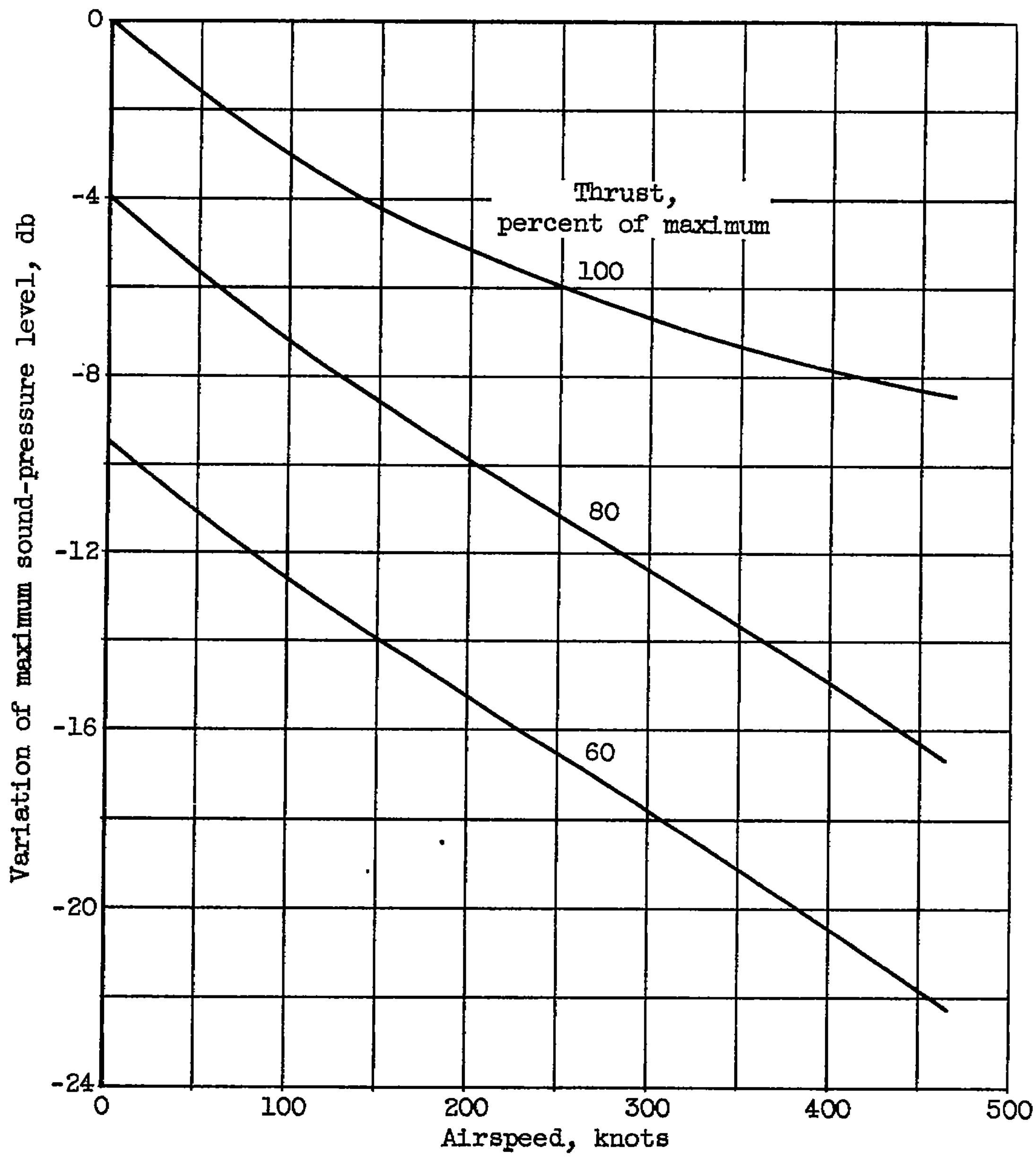

Figure 9. - Variation of maximum sound-pressure level with airspeed and thrust.

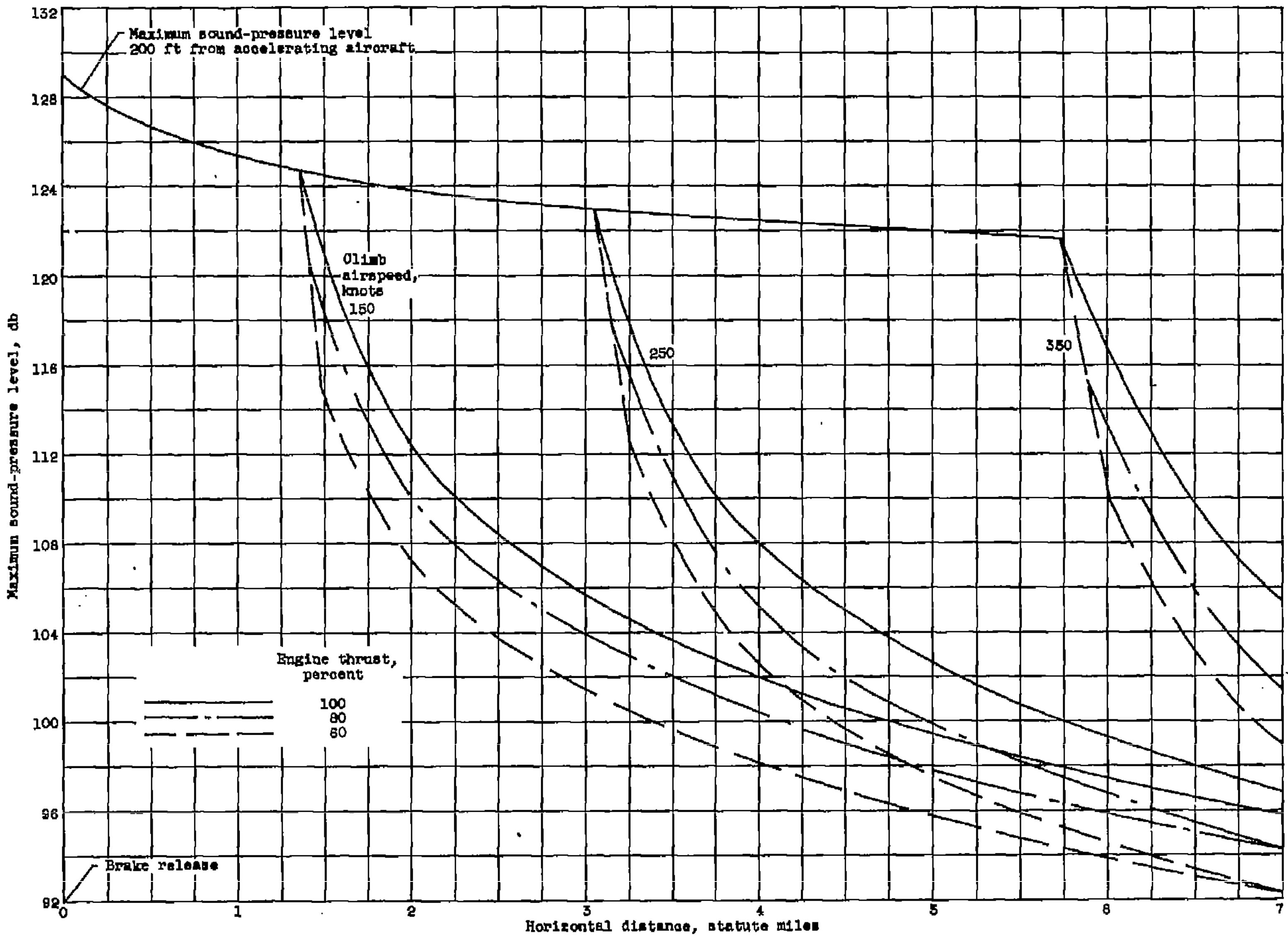

Figure 10. - Maximum sound-pressure levels under flight path at various values of airspeed and thrust.

NACA - Langley Field, Va.